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THE CAJON PASS SCIENTIFIC DRILLING EXPERIMENT: OVERVIEW OF PHASE 1

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Abstract. The Cajon Pass Scientific Drilling Project is a broad, interdisciplinary experiment involving over two dozen principal scientists. Phase I of drilling, coring and downhole experimentation began Dec. 8, 1986 and ended April 2, 1987 with the hole at a depth of 2115 m, 82 m of core recovered and a wide range of downhole experiments successfully completed. In this paper we briefly outline the scientific motivation for the project and provide an overview of the scientific program. We also indicate some of the varied research areas in the earth sciences where data obtained in this experiment will provide unique and important insight into active *in situ* processes, regional geologic structure, and rock and fluid composition and origin.

Introduction

One of the principal scientific objectives of the Cajon Pass project is to address a long-standing problem in fault mechanics sometimes referred to as the stress/heat flow paradox. Approximately 100 measurements of conductive heat flow near the San Andreas fault have detected no frictionally generated heat (Henyey, 1968, Brune et al., 1969; Henyey and Wasserburg, 1971; Lachenbruch and Sass, 1973; 1980), implying that the average shear stress acting on the San Andreas fault is less than about 20 MPa. This result conflicts with the average shear stresses that would be inferred from application of Mohr-Coulomb theory using laboratory-derived coefficients of friction (Sibson, 1974) and with *in situ* stress measurements (McGarr and Gay, 1978; Brace and Kohlstedt, 1980; McGarr et al., 1982; Pine et al., 1983; Zoback and Healy, 1984). These suggest that average shear stress values should be about 100 MPa, a factor of 5 higher than the upper bound permitted by the heat flow data. Resolution of this paradox is crucial to understanding the nature of deformation along major plate boundaries, the relevance of laboratory rock-friction experiments to crustal faulting and the balance of forces that drive and resist plate motion (Lachenbruch and Sass, 1973; Hanks, 1977). Various aspects of the stress/heat flow paradox have been recently discussed by Zoback et al. (1987), Henyey et al. (1988) and Lachenbruch and Sass (this issue).

The goal of the Cajon Pass project is to drill a vertical hole to a depth of 5 km in relatively intact basement rocks close to the San Andreas fault to address the stress/heat flow paradox and a number of other important scientific questions. In this special issue of Geophysical Research Letters, preliminary scientific results from the first phase of drilling and downhole testing to a depth of 2.12 km are described.

The origin of the Cajon Pass project is due, in large part, to Frederick Berry, a consulting geologist with Arkoma Production Co., who, in 1983, recognized the potential scientific value of a 1.7 km deep wildcat well to be drilled by Arkoma only 4.3 km from the San Andreas fault in the Cajon Pass area (Figs. 1,2). The Arkoma well was then turned over to the U.S. Geological Survey and utilized for heat flow measurements (Lachenbruch and Sass, this issue) and *in situ* stress measurements (Healy and Zoback, this issue) in 1984 and 1985 and has provided valuable geologic information about the site (Silver and James, this issue). Unfortunately, the Arkoma hole could not be deepened because of engineering constraints. In December 1986, Deep Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC), a non-profit consortium of 45 universities funded by the National Science Foundation, and working closely with the U.S. Geological Survey, undertook the Cajon Pass Scientific Drilling Project and drilling of the "DOSECC" well was begun at a site 50 m north of the Arkoma well.

The Cajon Pass drill site was chosen because of: (1) good exposure of local geology and moderate topographic relief at a site close to the San Andreas; (2) good-quality basement rocks in the area as indicated by a deep core, cuttings and geophysical logs from the Arkoma well; (3) the importance of this area for future fault zone monitoring (see below); (4) a number of practical considerations such as adequate space to work and access for drilling and supply equipment; and (5) the fact that the high long-term right lateral slip-rate on the San Andreas in the region (Weldon, 1986) and the existence of a 4.5 m, right-lateral fault slip event about 1812 (Weldon, 1986; K. Sieh, pers. comm.) indicates that the long-term fault behavior here is typical of most of the San Andreas.

The design depth of 5 km was chosen for a variety of reasons. First, it has been proposed that conductive heat flow measurements are not reliable indicators of shear stress magnitudes on the fault because of heat dissipation by convective heat transfer through fluid flow (O'Neil and Hanks, 1980). Five km represents a depth appreciably greater than that at which appreciable fluid movement is expected to affect the observed heat flow. Five km is also deep enough to minimize the effects of local erosion and topography on observed heat flow (Lachenbruch and Sass, this issue). Second, 5 km is sufficiently deep that the observed shear stresses should reflect the stress conditions under which major earthquakes occur on the San Andreas. At 5 km the high stress model of the San Andreas would predict the existence of about 40-50 MPa of right-lateral shear stress, whereas the low stress model would suggest right-lateral shear stresses less than 20 MPa. Third, by drilling to 5 km, we obtain data well below the depths at which either local or regional topography would have an appreciable effect on the observed stress field. Finally, as the hole's 5 km depth is much

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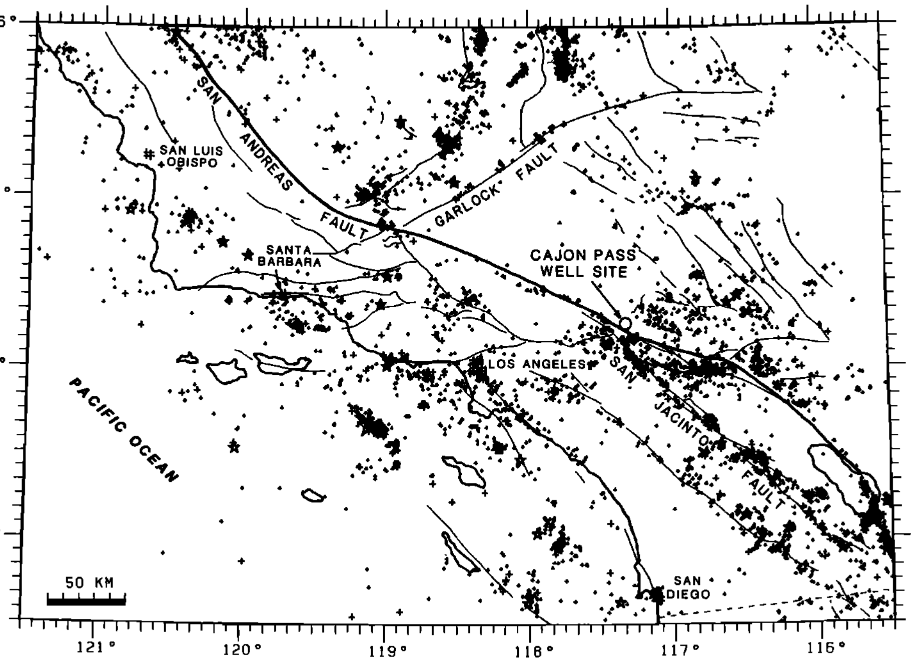

Fig. 1. Location of the Cajon Pass scientific research well along the San Andreas fault in Southern California. Seismicity is shown for a 5 year period (Map provided by Lucy Jones, USGS).

greater than its distance to the fault, the *in situ* measurements will be in the "near-field" of the San Andreas and thus will reflect stress and thermal conditions at seismogenic depths.

To address the stress/heat flow paradox, key elements of the scientific program include measurements of *in situ* stress magnitude and orientation utilizing the hydraulic fracturing and wellbore breakout techniques (Healy and Zoback, this issue; Shamir et al., this issue), heat flow and heat production (Lachenbruch and Sass, this issue; Williams et al., this issue), pore pressure and permeability (Coyle and Zoback, this issue; Morrow and Byerlee, this issue) and pore fluid chemistry (Kharaka et al., this issue; Evans, et al., this issue). A number of other studies are being conducted that provide important ancillary data for interpretation of the stress and heat flow data and for maximizing the scientific return of the overall project. A detailed geologic log of the hole (Silver and James, this issue),and a comprehensive set of geophysical logs (Anderson et al., this issue; Pezard et al., this issue; Pezard and Luthi, this issue) provide continuous lithologic and petrophysical information directly interpretable in the context of local geologic mapping (Weldon, this issue; Silver and James, this issue; Ehlig, this issue; Vincent and Ehlig, this issue). A comparison of these data in the Arkoma and DOSECC

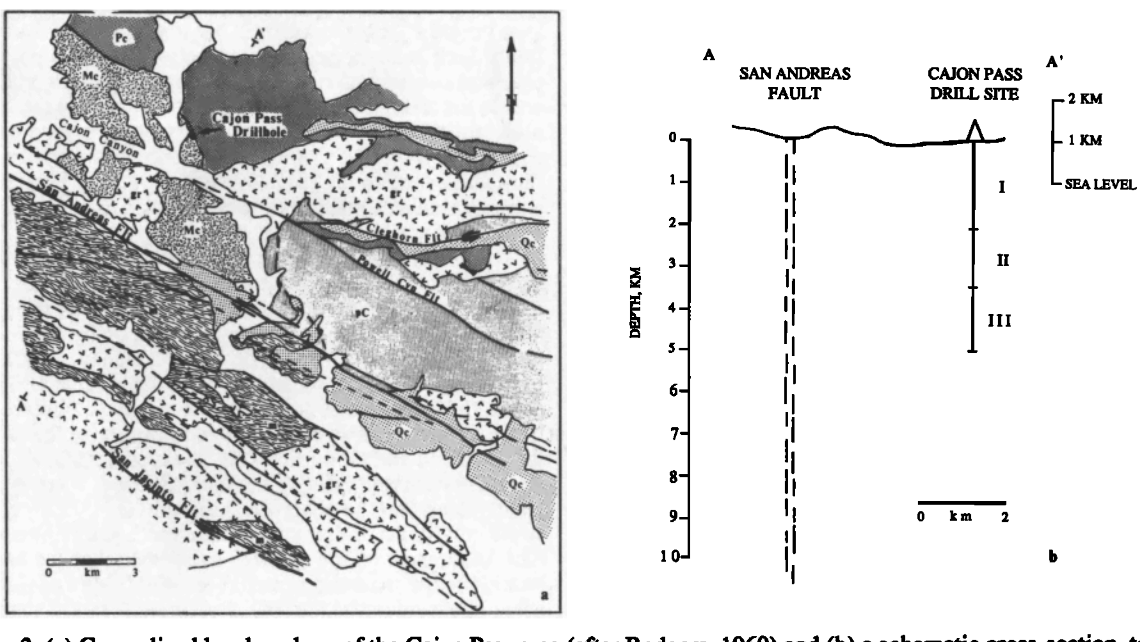

Fig. 2. (a) Generalized local geology of the Cajon Pass area (after Rodgers, 1969) and (b) a schematic cross-section to illustrate the distance and depth of the hole with respect to the San Andreas fault. The generalized rock units are: (PC) Precambrian igneous and metamorphic rocks; (gr) Mesozoic granitic rocks; (m) Pre-Cretaceous metamorphic rocks; (Mc) Miocene non-marine rocks; (Pc) Pliocene non-marine rocks; (Qc) Pleistocene and younger non-marine rocks.

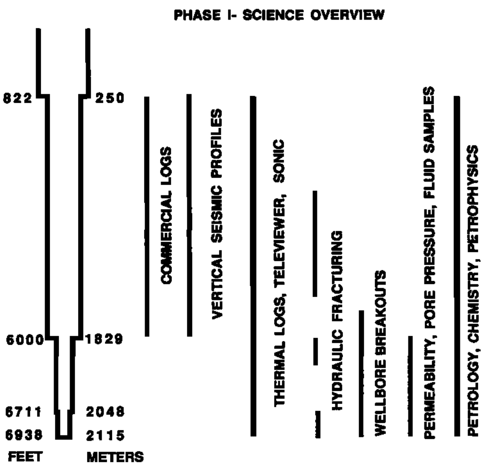

Fig. 3. Distribution of downhole measurements in Phase I of the Cajon Pass project.

holes provide an important control on local and regional geology (Silver and James, this issue; Pezard et al., this issue). Vertical seismic profile data (Li et al., this issue; Daley et al., this issue; Rector, this issue) are used to study stress-induced velocity anisotropy around the borehole and, when coupled with P-wave seismic reflection profiling in the area, are used to map local geologic structures in the vicinity of the drill site. Because natural fracture systems are important as indicators of crustal deformation and have important effects on crustal properties, fractures and fracture mineralization in the cores are described (Silver and James, this issue; Vincent and Ehlig, this issue) and wireline geophysical measurements are used to provide important information on the distribution and orientation of natural fractures throughout the hole (Barton and Moos, this issue; Pezard and Luthi, this issue; Moos, this issue).

The Cajon Pass experiment has several important implications for earthquake prediction research. First, resolution of the stress/heat flow paradox is key to understanding the mechanics of crustal faulting. For example, if the experiment were to find high stress and high heat flow at depth it would basically confirm applicability of scores of laboratory studies and theoretical modeling, based on the laboratory research, to the process of crustal faulting. Conversely, if the experiment were to confirm the implications of the heat flow data and indicate extremely low shear stresses on the fault, it would imply that faulting was being controlled by fault zone materials with dramatically different deformational properties than those used in most of the laboratory experiments (see Zoback et al., 1987; Lachenbruch and Sass, this issue; Wang, this issue). Understanding fault zone properties is critical for establishing a physical basis for earthquake prediction. As described in the papers in this issue by Healy and Zoback, Lachenbruch and Sass, and Shamir et al., preliminary data from the Cajon Pass experiment appear to support the low shear stress model of the San Andreas. The Cajon Pass experiment also pertains to earthquake prediction through utilization of the borehole for long-term fault zone monitoring. The significant likelihood (Sieh et al., 1988) of a major earthquake on the western Mojave section of the 1857 break, the section of the San Andreas immediately northwest of Cajon Pass, and the high population density close to the fault in this area indicate that this is an extremely important section of the fault for concentrated fault zone monitoring efforts. The opportunity of monitoring seismicity and crustal strain at ~5 km depths is unprecedented in earthquake prediction research, permitting the testing of new instrumentation at these depths, direct comparison of shallow and deep monitoring results and offering the potential for new insight into fault behavior. At the end of drilling the DOSECC hole will be turned over to the U.S. Geological Survey for these purposes in conjunction with similar activities of the USGS in the region.

Experimental Design and Implementation - Phase I

The experimental design in a project such as this represents trade-offs among scientific, engineering and economic considerations. One of the most difficult decisions concerned the science plan in the upper part of the hole. Because of the operational necessity to set casing to a depth of 1.83 km a large diameter (31.8 cm) hole was drilled to that depth and only a limited amount of core was obtained (57.9 m) representing 3.2% recovery. Below 1.83 km, 24.2 m (8.5%) of core was recovered. While only a small fraction of the hole was cored, the samples are invaluable for geologic and geochemical studies, for studies of rock strength needed for interpretation of the hydraulic fracturing and wellbore breakout stress measurements, for studies of petrophysical properties, fractures and deformational microfabrics and for calibration of geophysical and geochemical logging methods. At the time of this writing, about 2000 samples have been distributed to different members of the science team. Furthermore, a continuous synthesis of cuttings and core information was prepared by L.T. Silver and E.W. James and distributed to all the investigators involved in the Cajon Pass project. This information (Silver and James, this issue) provides the basis for many of the interpretations that appear in this issue.

The distribution of scientific studies in the hole is illustrated in Fig. 3. Prior to setting the casing at 1.83 km, a comprehensive set of logs were run including newly-developed geochemical logs and formation imaging tools (Anderson et al., this issue; Pezard and Luthi, this issue) and three-component magnetometer, magnetic susceptibility and borehole radar logs. Repeated temperature measurements (Lachenbruch and Sass, this issue), ultrasonic borehole televiewer (Barton and Moos, this issue; Shamir et al., this issue) and full-wave sonic logging (Moos, this issue) were done from 0.25 km (the depth of a shallow casing string) to 2.12 km. The borehole televiewer logging has provided extensive data on stress orientation from wellbore breakouts in the lower 440 m of the well (Shamir et al., this issue). At the end of Phase I drilling and testing, two different vertical seismic profiling experiments were performed in the upper 1.83 km. Results from the first experiment that utilized P- and S-wave vibrators and multiple three-component receivers are described by Daley et al. (this issue), Leary et al.(this issue) and Li et al. (this issue). Data acquisition and preliminary results of a second experiment utilizing a multi-component impact source and a gyroscopically-oriented three-component receiver are described by Rector (this issue). Two types of permeability and pore pressure measurements were conducted in the well and are described by Coyle and Zoback (this issue) and Kharaka et al. (this issue).

Impacts of Cajon Pass Research

The Cajon Pass project has provided critical data for scientists in a wide range of disciplines. When one considers the large number of scientists involved in the project and the broad range of research fields involved, scientific drilling becomes quite cost effective, especially since most of the data cannot be obtained any other way. The shear stress required to cause movement along major plate-bounding faults has broad application to other continental transform faults, oceanic transforms (see discussion by Lachenbruch and Sass, this issue; Lachenbruch and Thompson, 1972; Lachenbruch, 1976), and potentially to subduction zones, low-angle thrusts and detachment faults. Similarly, the state of stress along plate boundaries is a fundamental boundary condition for models of plate driving forces and lithospheric flexure. If the final results of this experiment indicate that the low stress model of the fault is correct, the relevance of numerous laboratory studies of friction to *in situ* conditions along major faults like the San Andreas is in doubt. Understanding the mechanics of faulting is crucial for progress in earthquake prediction, strong-motion seismology and in constraining theories of the origin of intraplate earthquakes.

Obtaining data on the three dimensional rock type distribution in the Cajon Pass experiment and the geochemical and geochronological signatures of the rocks and geological structure, helps constrain concepts of local and regional geologic evolution (Silver and James, this issue; Ehlig, this issue; Pezard et al., this issue). Also the identification and verification of seismic reflectors as a means of advancing the interpretation of crustal seismic profiles (Leary et al., this issue) is extremely important for crustal seismic reflection studies. The extensive vertical seismic profile data, coupled with local seismic reflection profiles, borehole sonic logs and core velocitiy measurements will yield critical data on the origin of reflectors in crystalline rock and of seismic anisotropy. The Cajon Pass results also have important implications for broad scale geologic processes such as the role of mid-crustal detachments along the plate boundary (Lachenbruch and Sass, 1973; 1980), formation of older low-angle fault structures (Ehlig, 1968; Silver,1982), the origin of transpression and transtension (Zoback et al., 1987; Mount and Suppe, 1987) and understanding the evolution of fractures and deformational fabric in rocks bounding a major fault system.

Not only are the hydrologic studies important relative to the stress/heat flow paradox, but they also provide important constraints on values of bulk permeability and pore pressure of basement rocks in the upper crust. The abundant quantities of pore fluid extracted from the Cajon Pass hole are unprecedented for crystalline rocks at this depth and the suite of ~80 chemical and isotopic analyses planned for the pore water and gas will provide abundant new data to constrain theories on the origin and evolution of deep crustal pore fluids. The core, cuttings and geophysical logs have provided an important insight into the role of zeolite deposition in controlling fracture permeability and fluid chemistry (Silver and James, this issue; Vincent and Ehlig, this issue).

Finally, utilization of the hole as an observatory for monitoring the San Andreas fault at depth holds unparalleled potential. Crustal strain and (micro)seismicity has never been measured at seismogenic depths near an active fault, and it is exciting to anticipate the kinds of data that may come from the hole in the future.

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